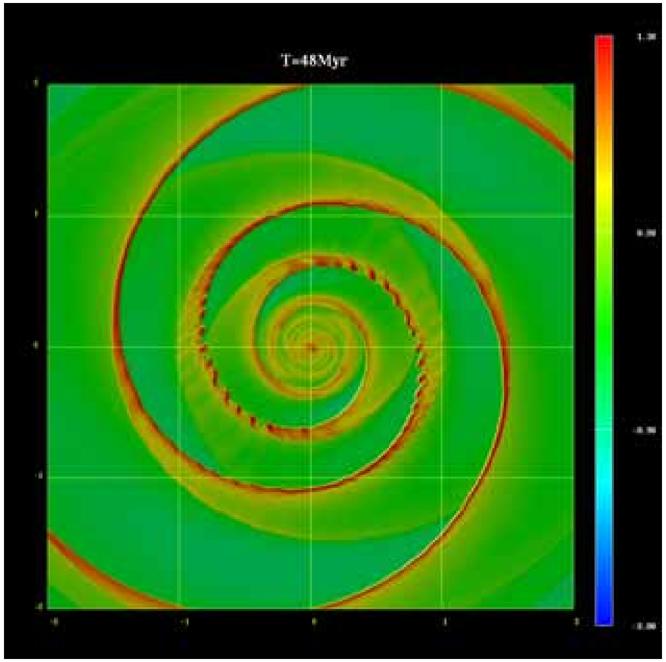
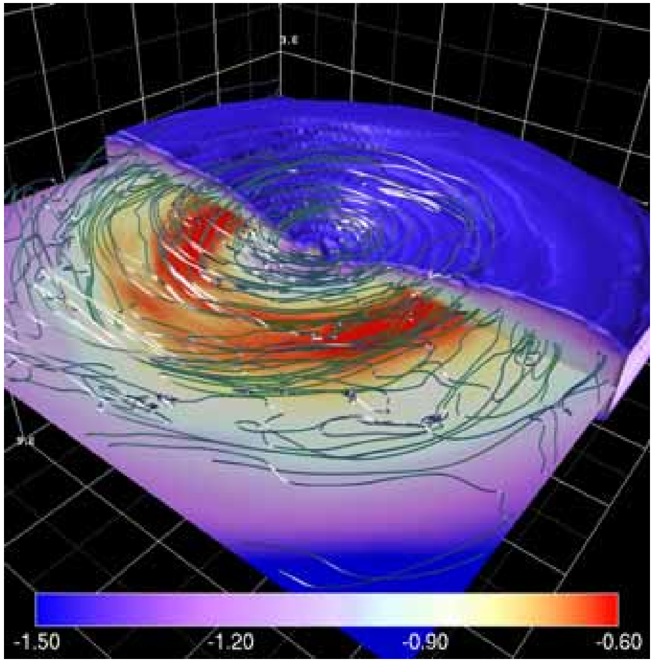
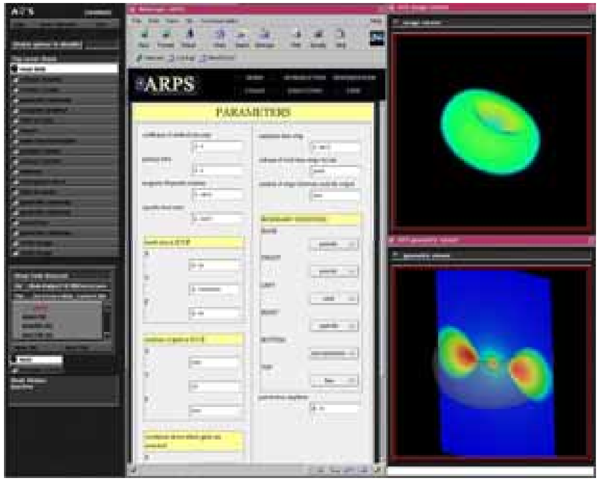
Global MHD Simulations of Galactic Gas Disks

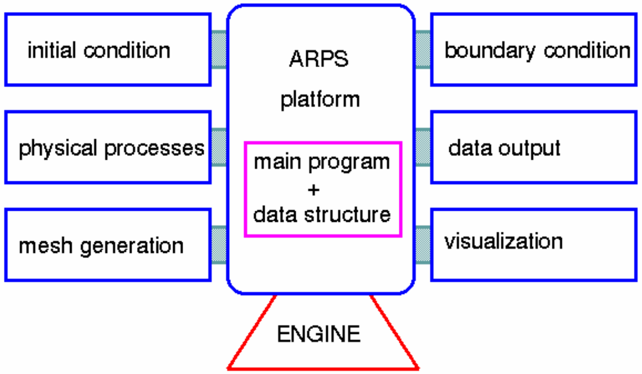


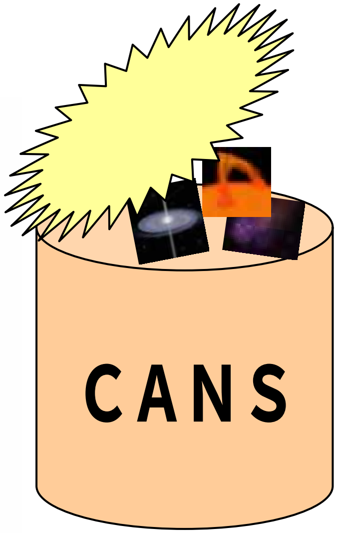


Ryoji Matsumoto (Chiba University)

Global Simulators of Astrophysical Rotating Plasmas







ARPS (Astrophysical Rotating Plasma Simulator, Matsumoto et al. 1999)

Coordinated Astronomical Numerical Software(CANS): product of ACT-JST project (2000-2002)

Basic Equations

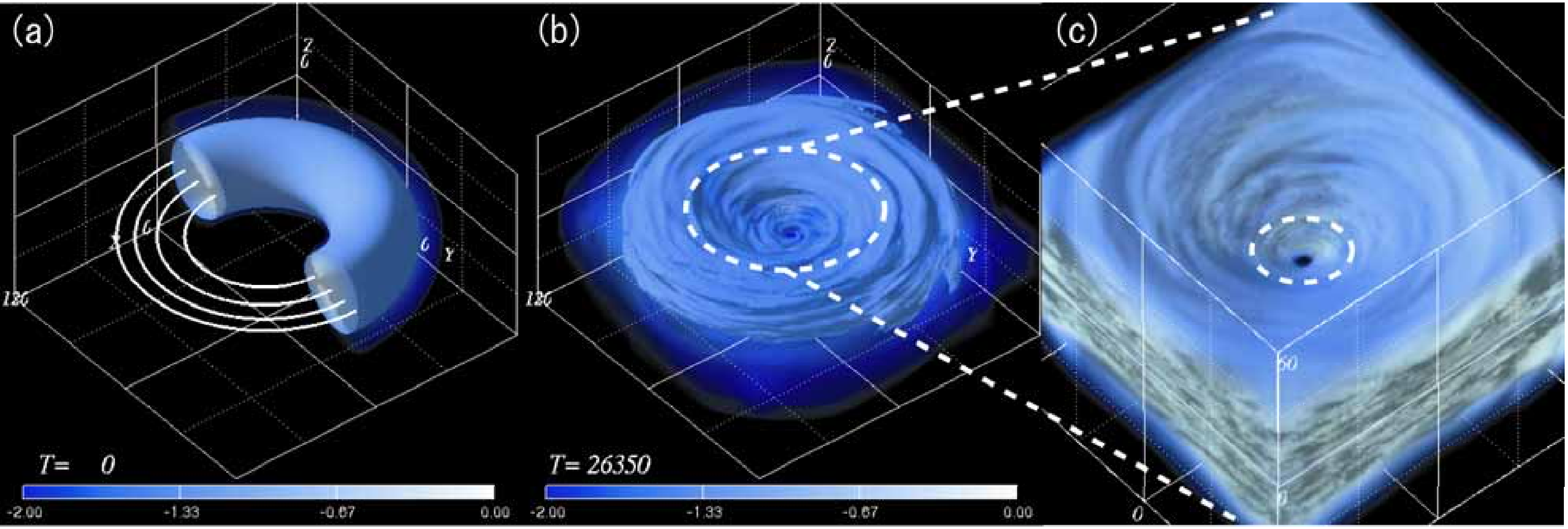
$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \bullet \nabla)\mathbf{v} = -\nabla P + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} + \rho \mathbf{g}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla(\rho \varepsilon \mathbf{v}) + P \nabla \mathbf{v} = Q_J + Q_{vis} - Q_{rad}$$

Formation of an Accretion Disk

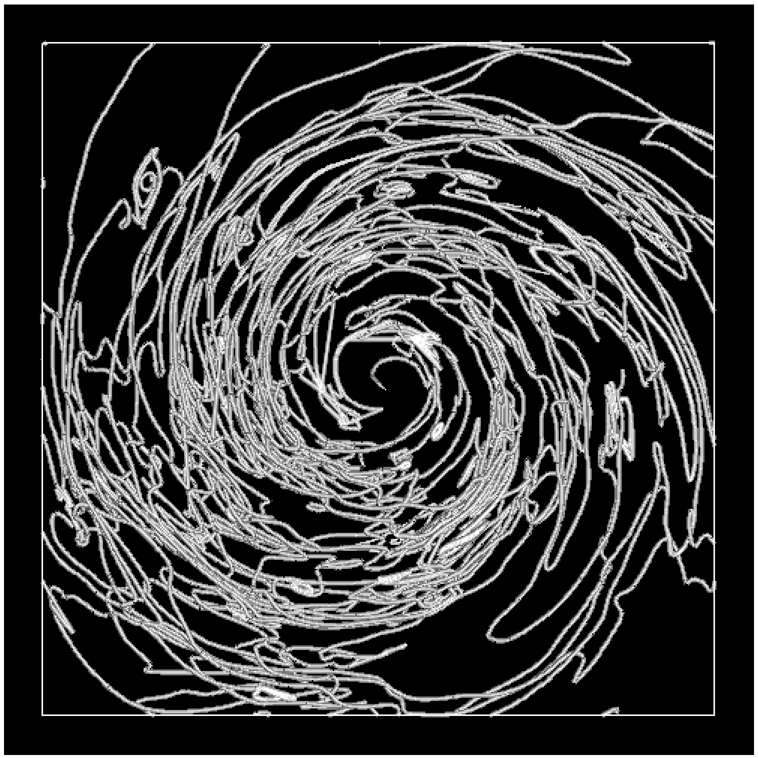


Initial state t=26350 unit time t_0=rg/c

Magnetic Field Lines

Magnetic field lines projected onto the equatorial plane

(-60 < x,y < 60)



Outer region

(-10 < x,y < 10)

Inner region

Magnetic field lines are tightly wound.

⇒ Turbulent motions are dominant in the disk.

Magnetic field lines are less turbulent and globally show bisymmetric spiral shape (BSS).

Outline of this Talk

- MHD Simulations of the wiggle instability in Galactic gas disks (M. Tanaka, M. Machida, K. Wada and R. Matsumoto 2005)
- Global 3D MHD Simulations of Galactic gas disks (H. Nishikori, M. Machida and R. Matsumoto 2005)

MHD Simulations of the Wiggle Instability in Galactic Gas Disks

Dark spur-like structures exist perpendicular to the spiral arms

By carrying out 2D global hydrodynamic simulations, Wada and Koda (2003) found that spur-like structures are created behind the spiral shock

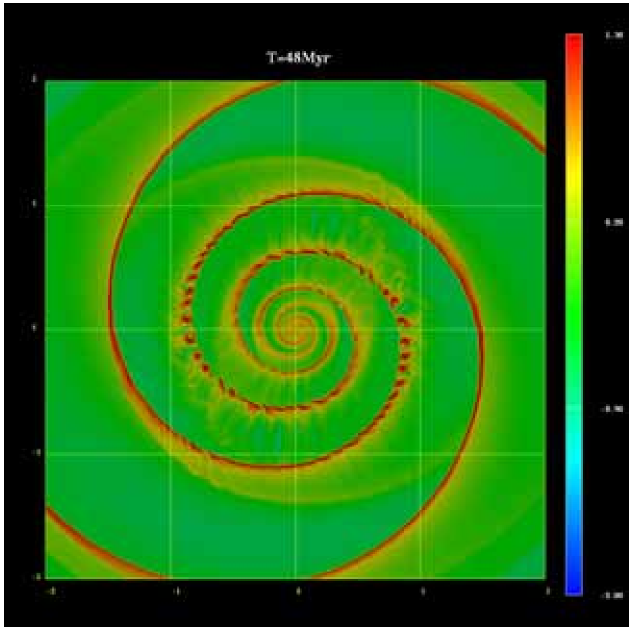
Global Simulations of the Wiggle Instability

- Gravitational Potential

$$\Phi(r,\phi) \equiv \Phi_0(r) + \Phi_1(r,\phi)$$

$$\Phi_0(r) \equiv a v_a^2 \left(\frac{27}{4}\right)^{1/2} (r^2 + a^2)^{-1/2}$$

$$\Phi_1(r,\phi) \equiv \varepsilon_0 \frac{a r^2 \Phi_0}{(r^2 + a^2)} \cos\left[2\phi + 2\cot i \cdot \ln(r)\right]$$



- Isothermal gas
- Neglect self-gravity
- Initially uniform gas
- axisymmetric part of gravity balances with rotation at the initial state

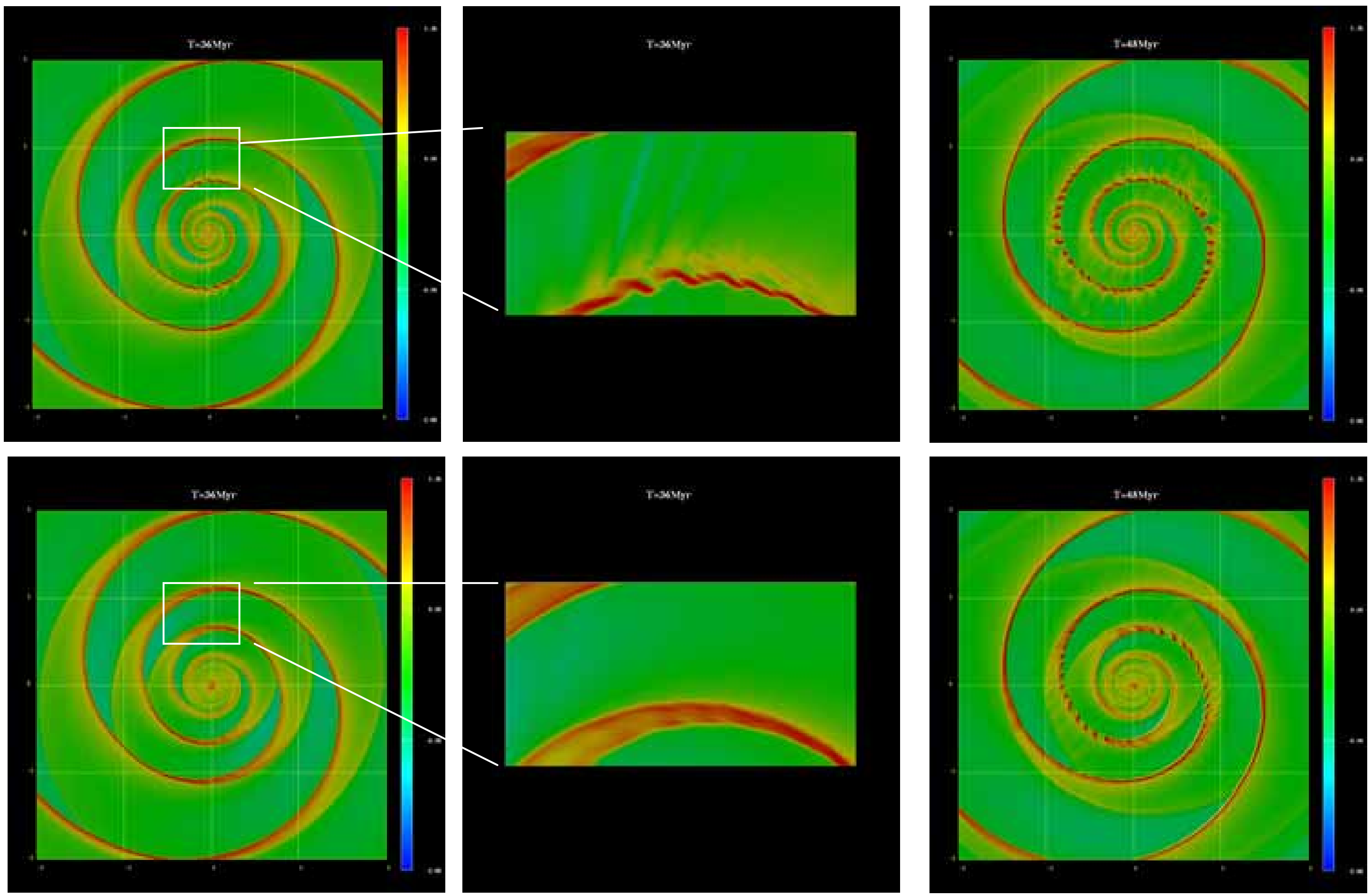
Global MHD Simulations of the Wiggle Instability

- We assume initially force free, toroidal magnetic fields:
  $\boldsymbol{\beta}$=Pgas/Pmag=10 at r=1kpc
- Simulation Code : CANS
- Simulation Engine : MLW
- Simulation region : 4kpc × 4kpc
- Number of Grid Points: 2048×2048

Numerical Results

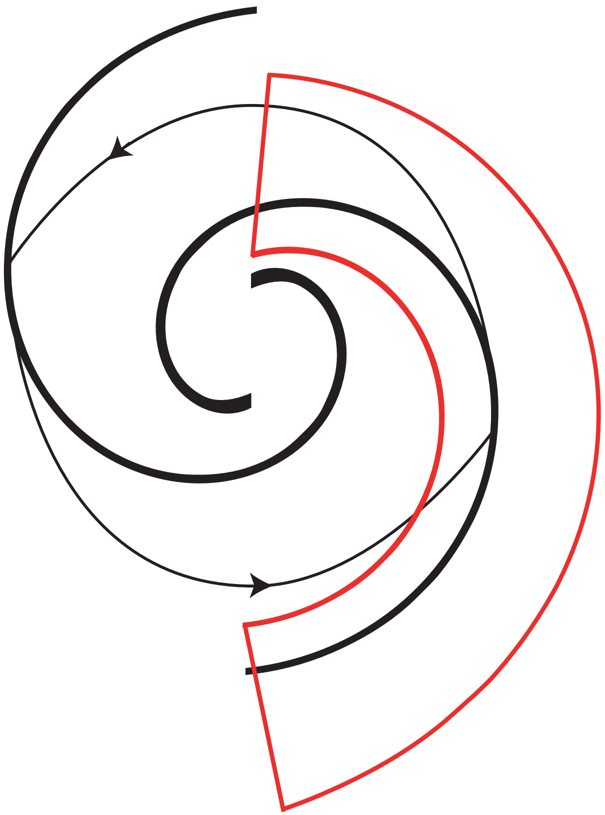
HD Model

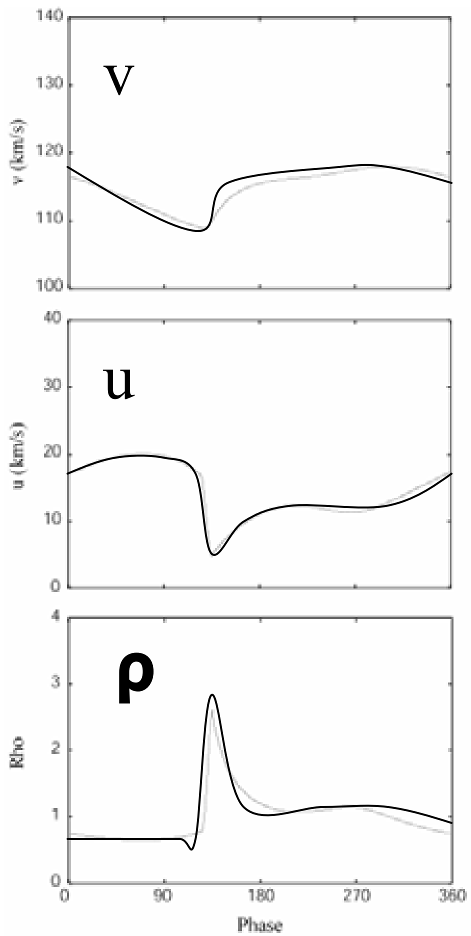
MHD Model

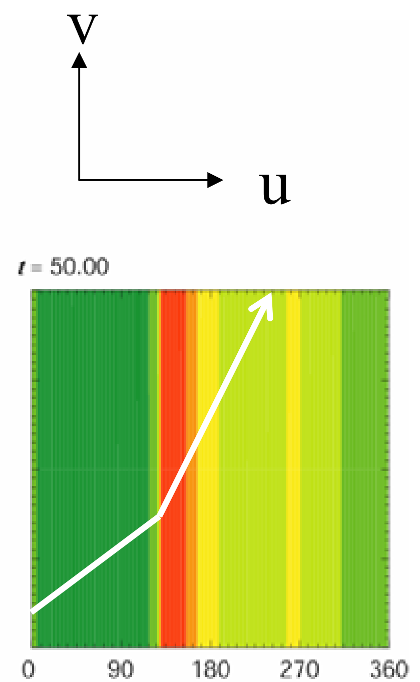


T=36Myr enlarged (36Myr) T=48Myr

Local Simulations of the Wiggle Instability: Are Global Effects Essential ?



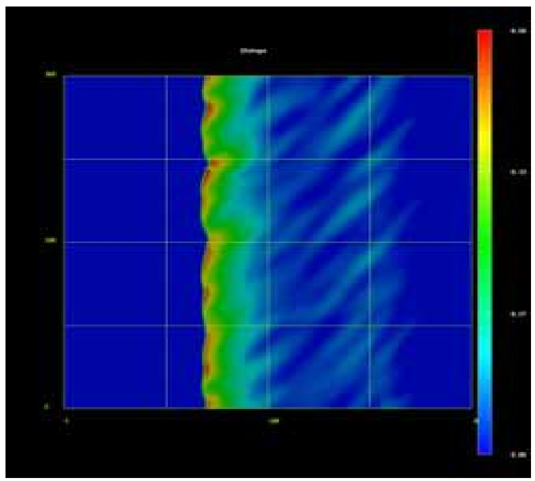




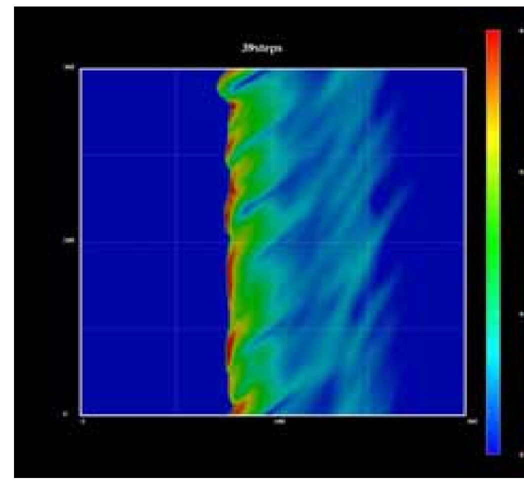
1D steady solution of galactic spiral shock (van Albada et al. 1982)

Numerical Results for Hydrodynamical Model

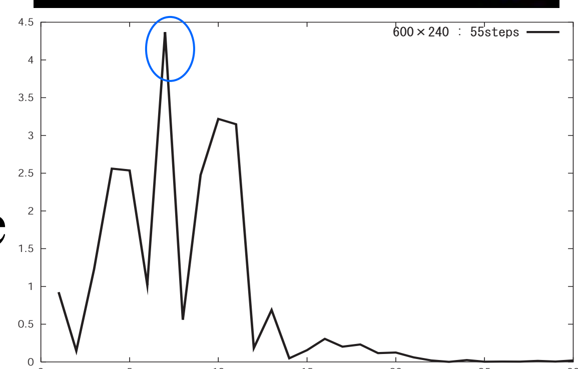
600✕240 mesh



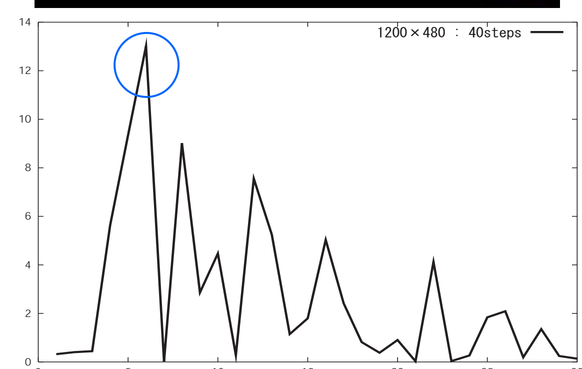
1200✕480 mesh



Fourier Amplitude



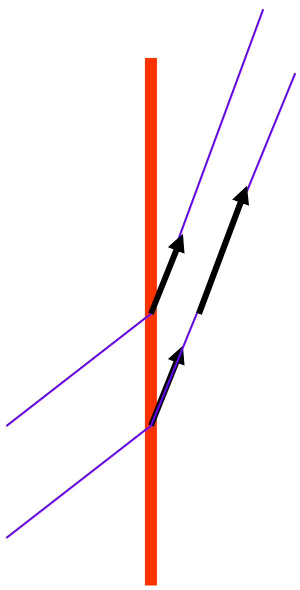
Mode number

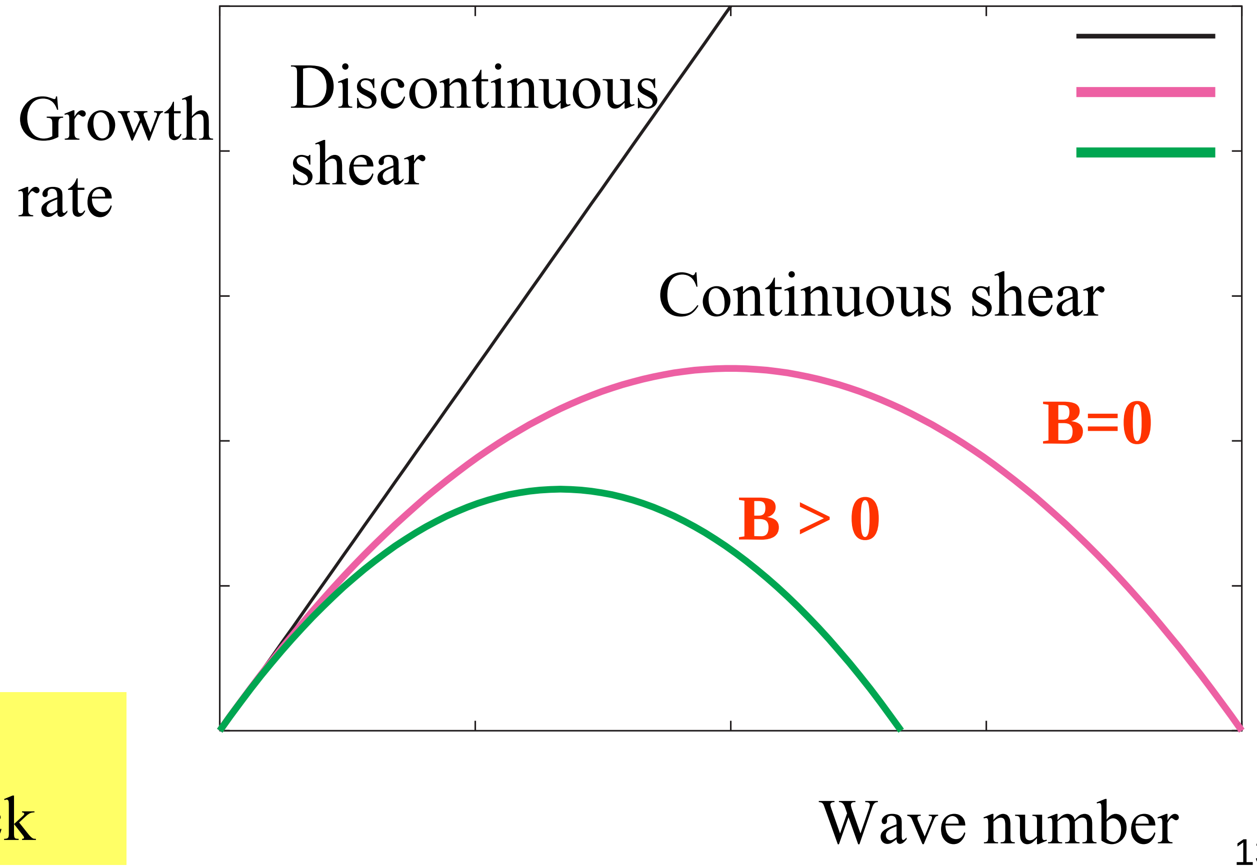


Mode number

Mechanism of the Instability

Spiral shock

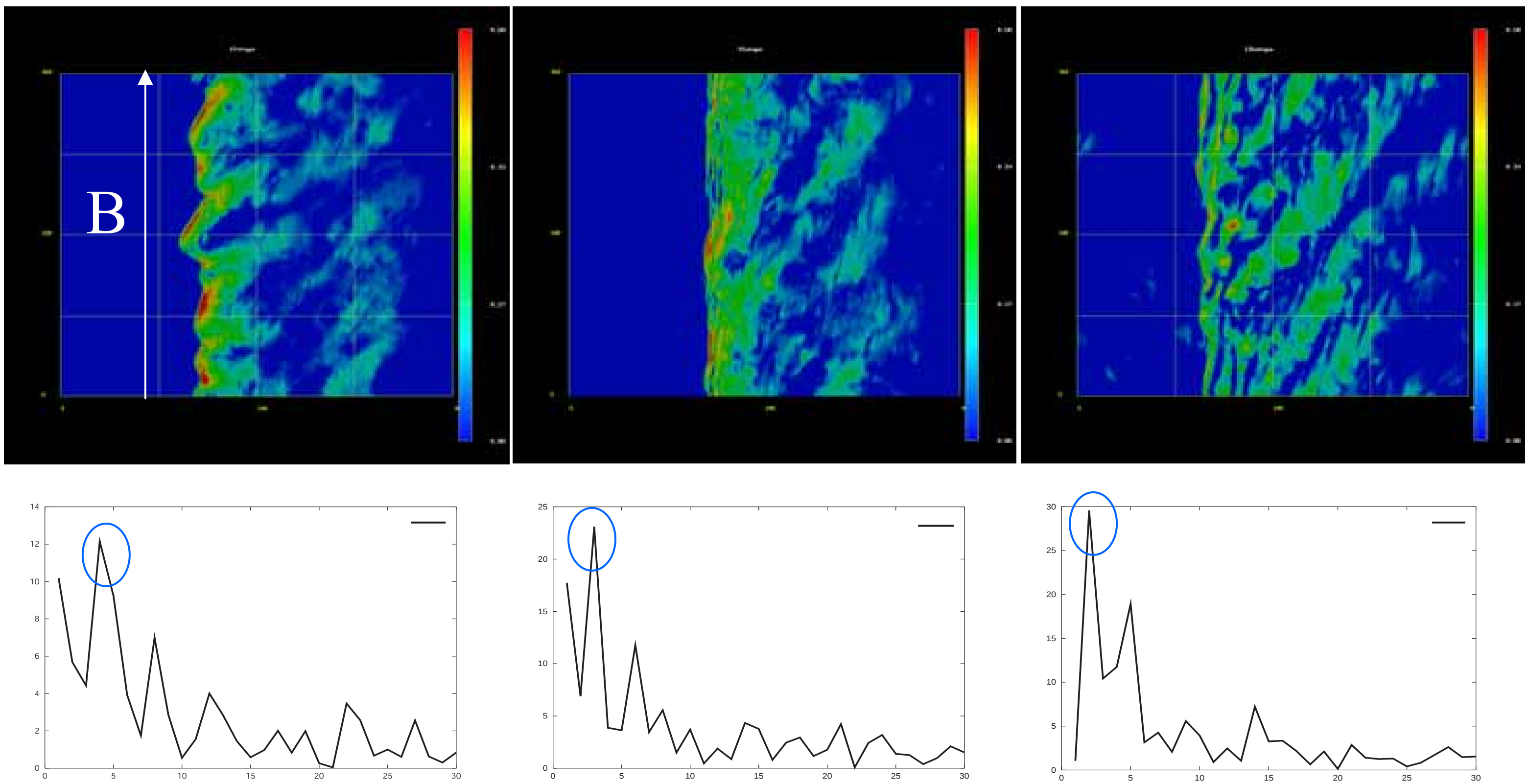




KH instability
behind the shock

Numerical Results for MHD Models

Weak field ⟷ Strong field



600×240 mesh

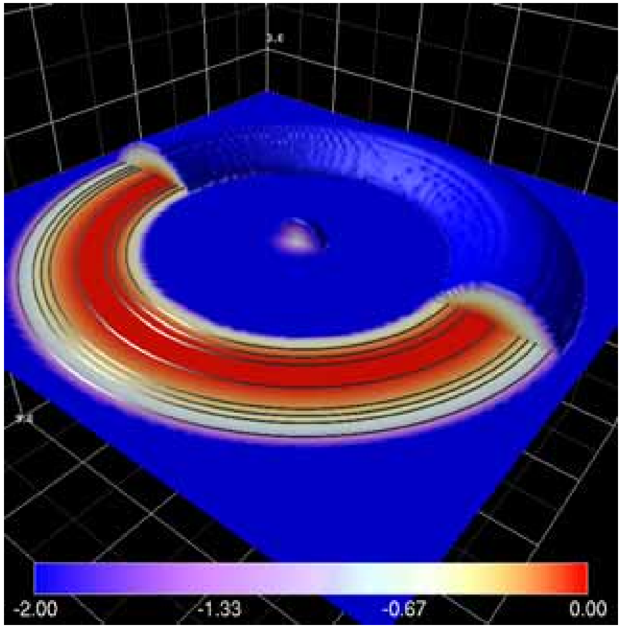
β＝1000
k＝4

β＝100
k＝3

B＝5
k＝2

Global 3D MHD Simulations of Galactic Gas Disks

- Gravitational Potential
  - Axisymmetric potential given by Miyamoto (1980) including dark matter
- Initial state
  - Constant angular momentum torus at 10kpc
  - Weak toroidal magnetic field (β=100,1000)
- Anomalous resistivity
- Absorbing boundary at r=0.8kpc

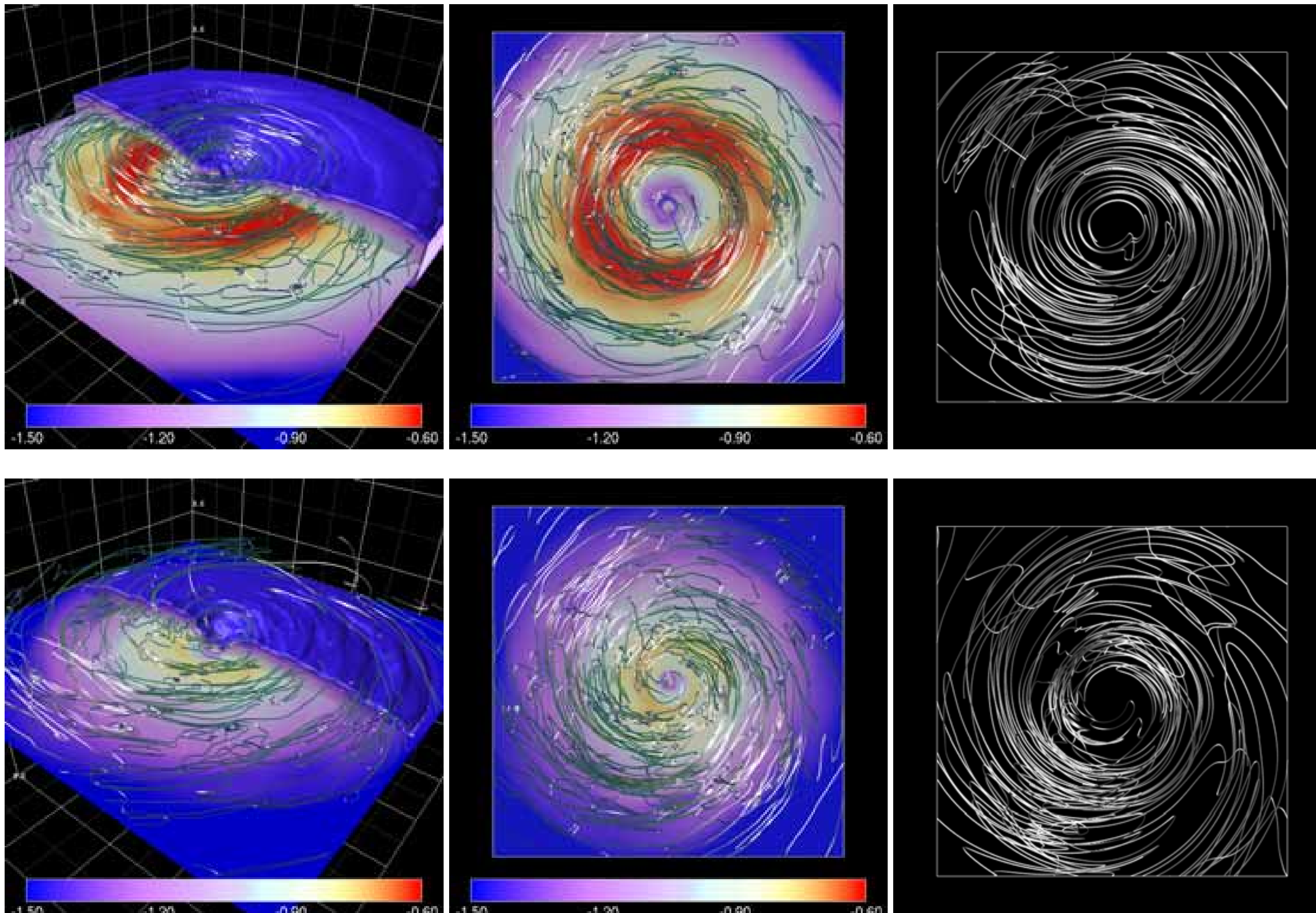


250*64*319 mesh

Numerical Results (β =100)

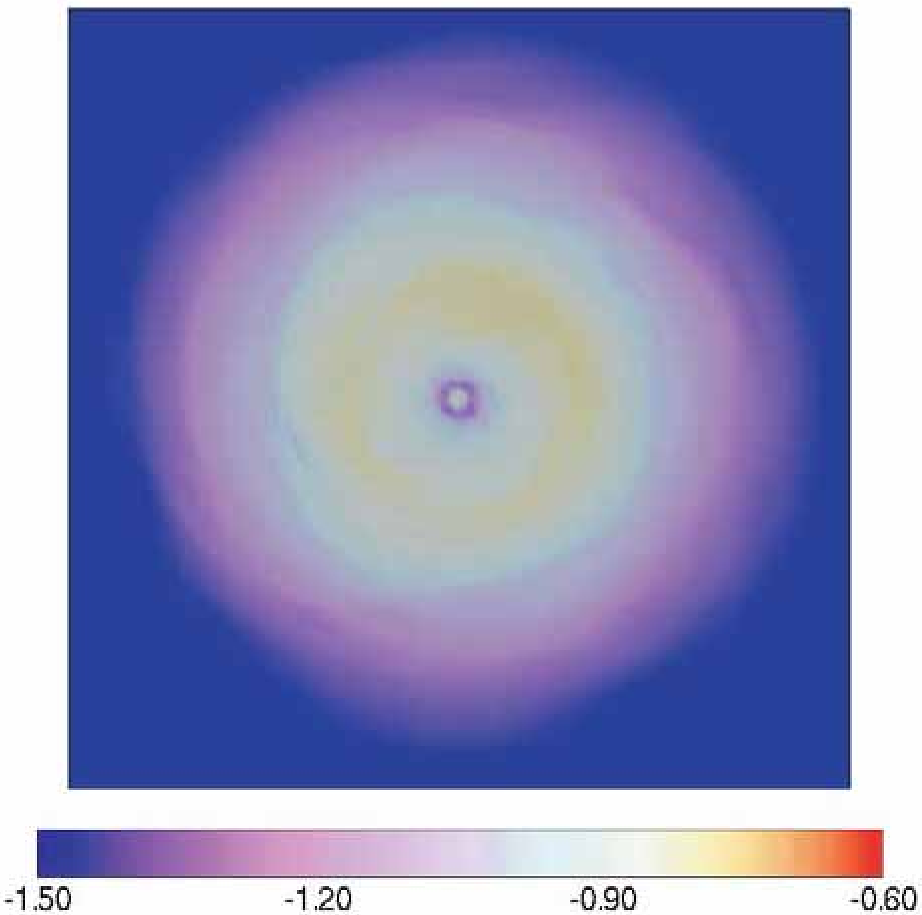
2Gyr

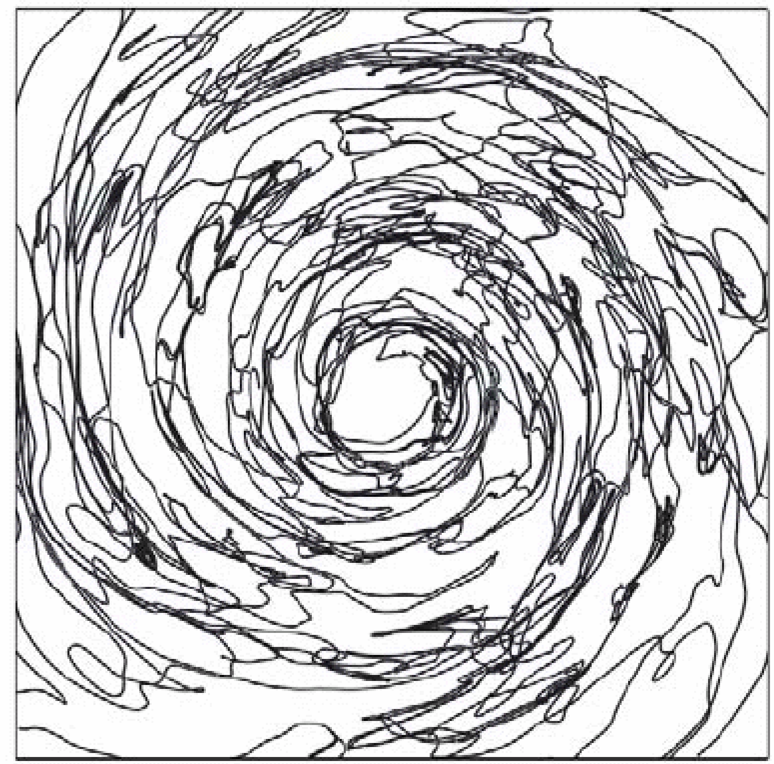
3.5Gyr



ρ + B   Raw field   Mean field

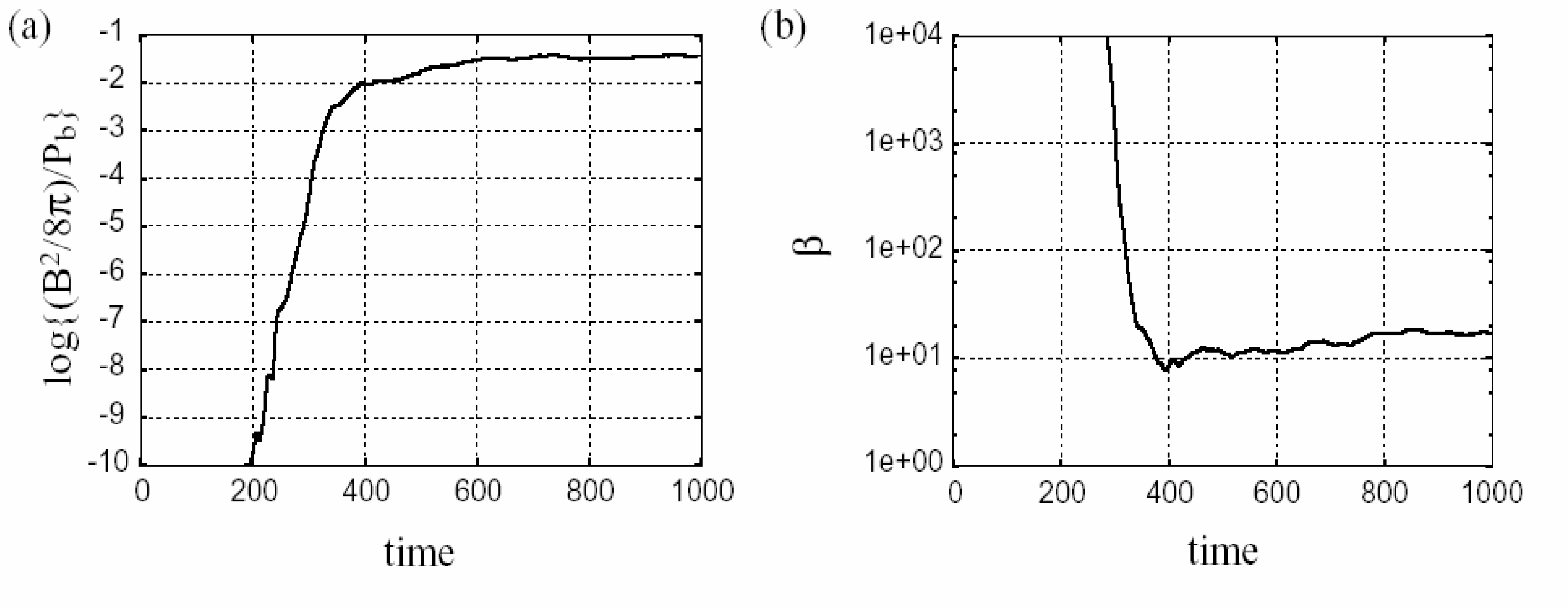
Density Distribution and Magnetic Field Lines





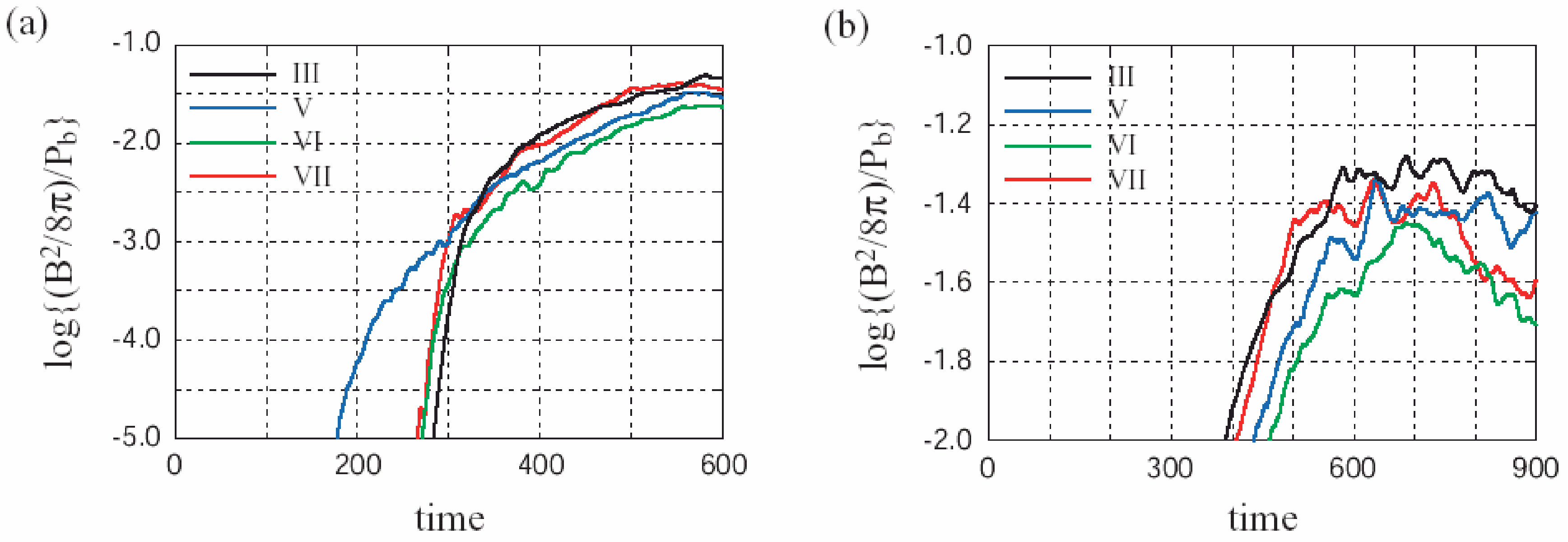
t = 3.8Gyr

Growth of Magnetic Field



Average in 2kpc < r < 5kpc and 0 < z < 1kpc

Dependence on Azimuthal Resolution and Simulation Region

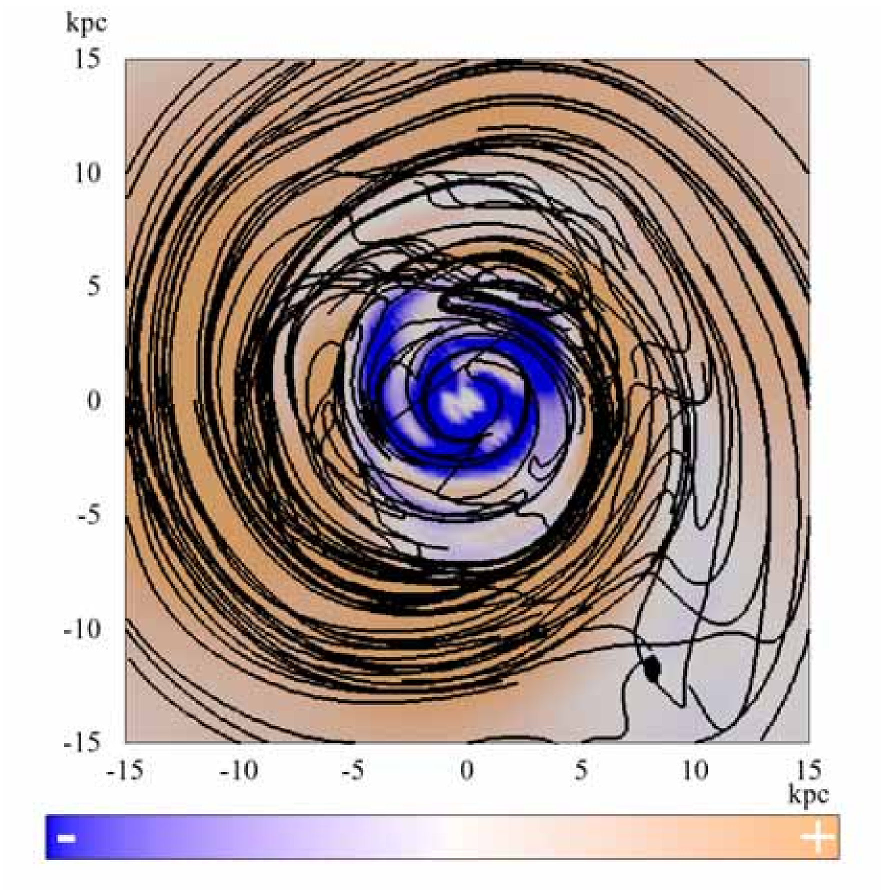


Model III: Full Circle Simulation with $\Delta\phi=2\pi/64$

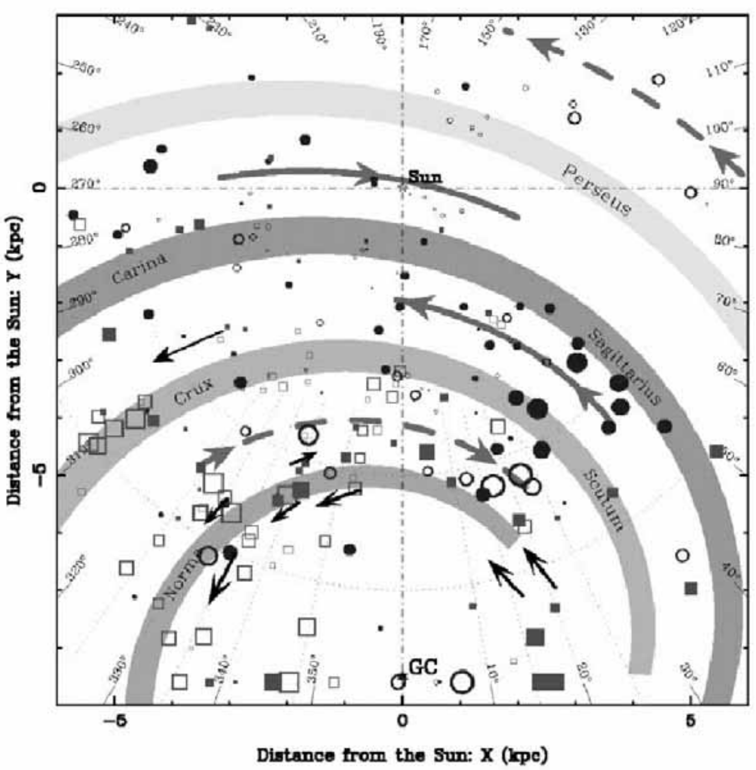
Model V-VII: ¼ Circle Simulation ($0 < \phi < \pi/2$) with

V: $\Delta\phi=\pi/128$ VI: $\Delta\phi=\pi/64$ VII: $\Delta\phi=\pi/32$

Reversal of Azimuthal Magnetic Field



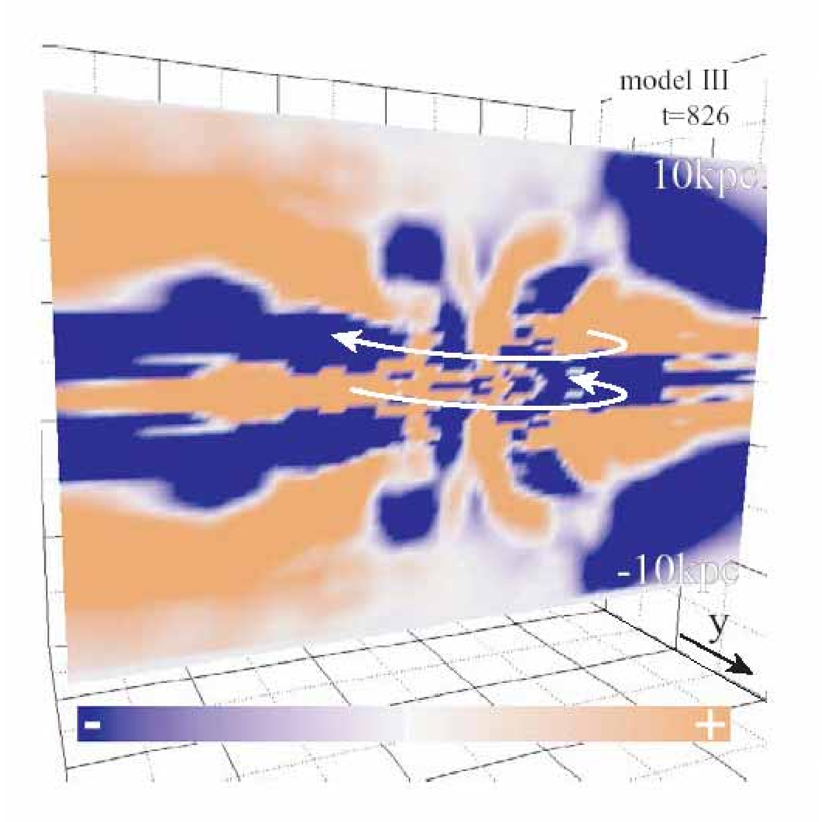
Azimuthal field at t=3.8Gyr at z=0.25Kpc



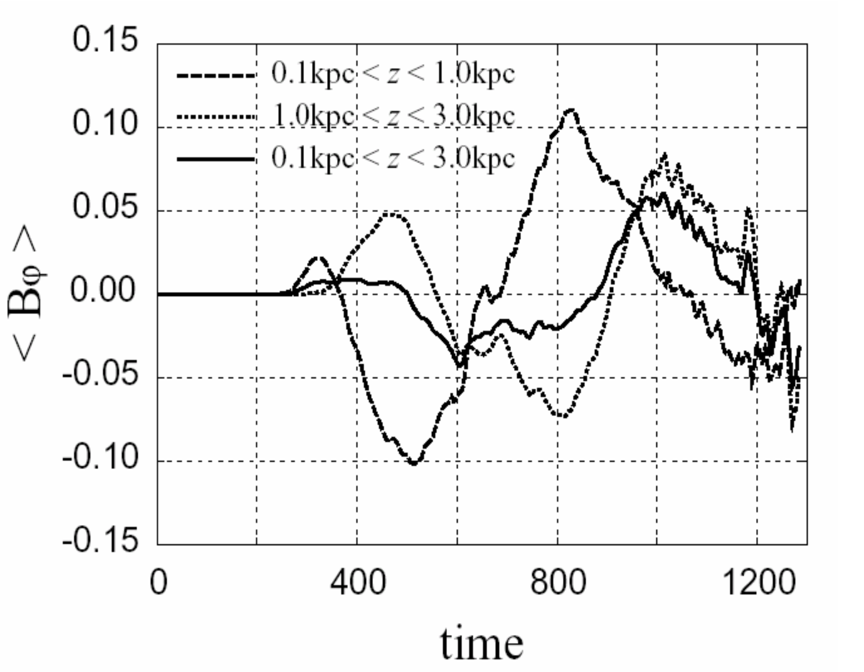
Galactic magnetic field obtained by Rotation Measure

(Han et al. 2001)

Spacial and Temporal Reversal of Azimuthal Magnetic Fields

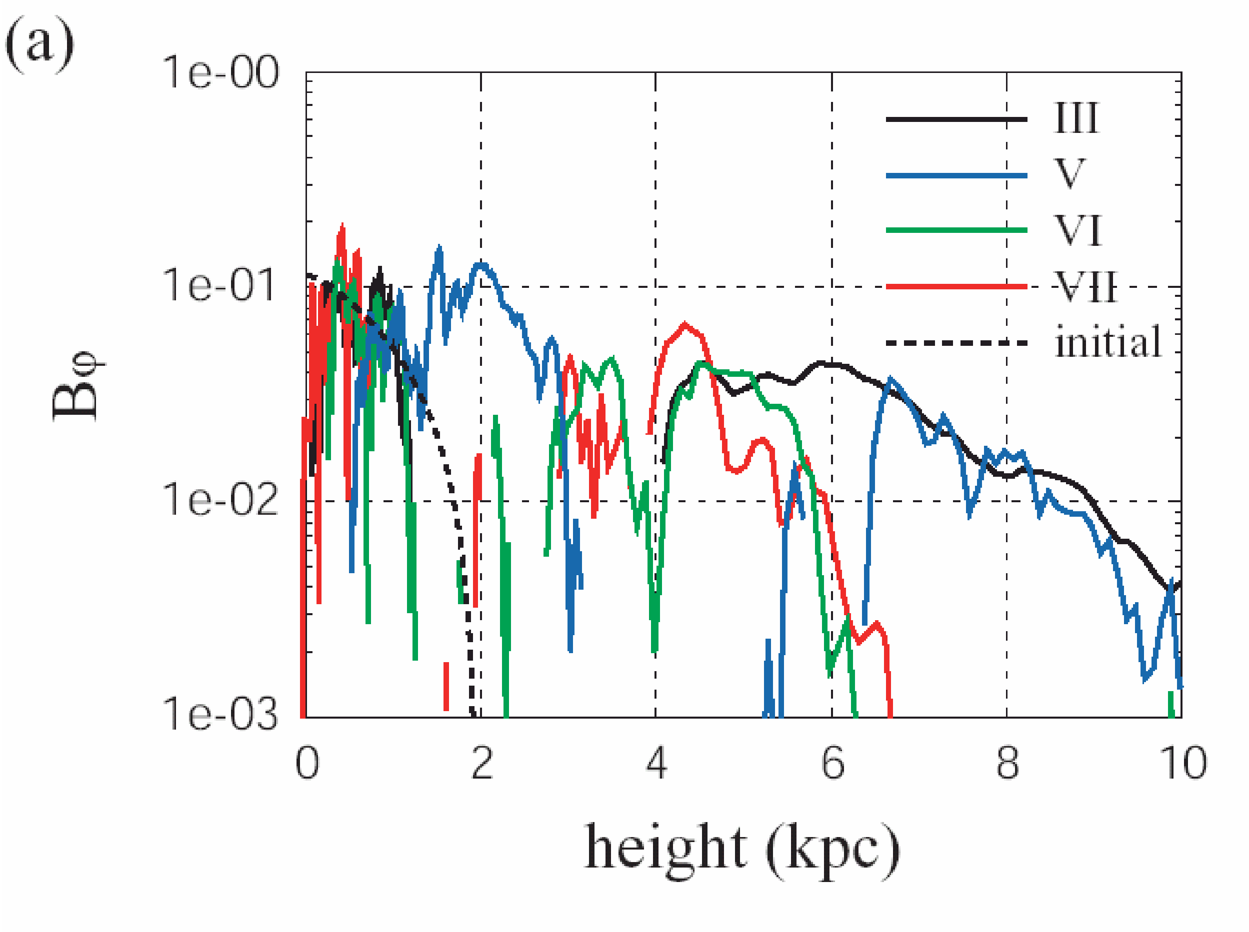


Azimuthal Magnetic Field at t=3.1Gyr



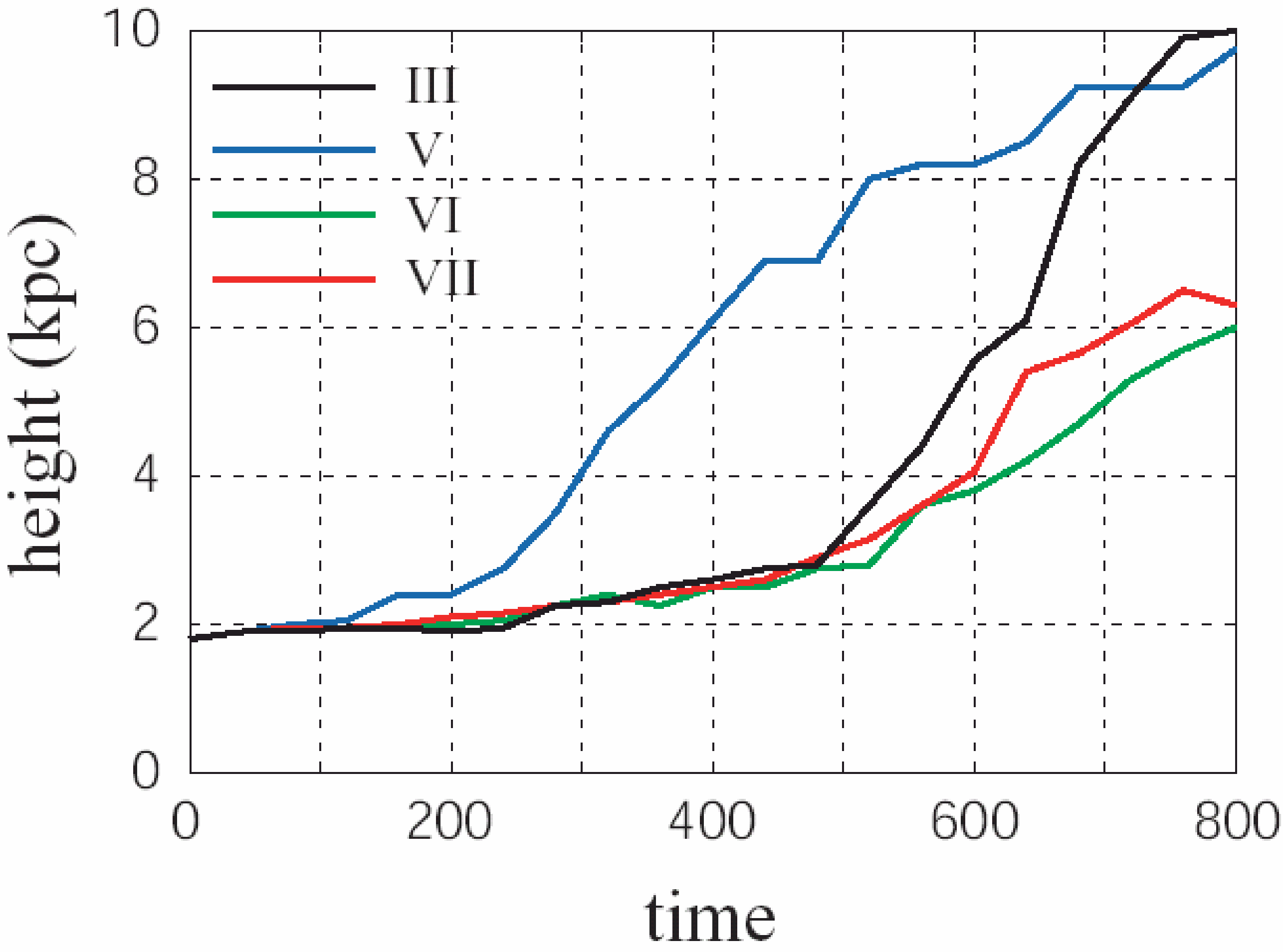
Time variation of mean azimuthal field at 5kpc < r < 6kpc and 0 < z < 1kpc

Buoyant Rise of Azimuthal Magnetic Flux

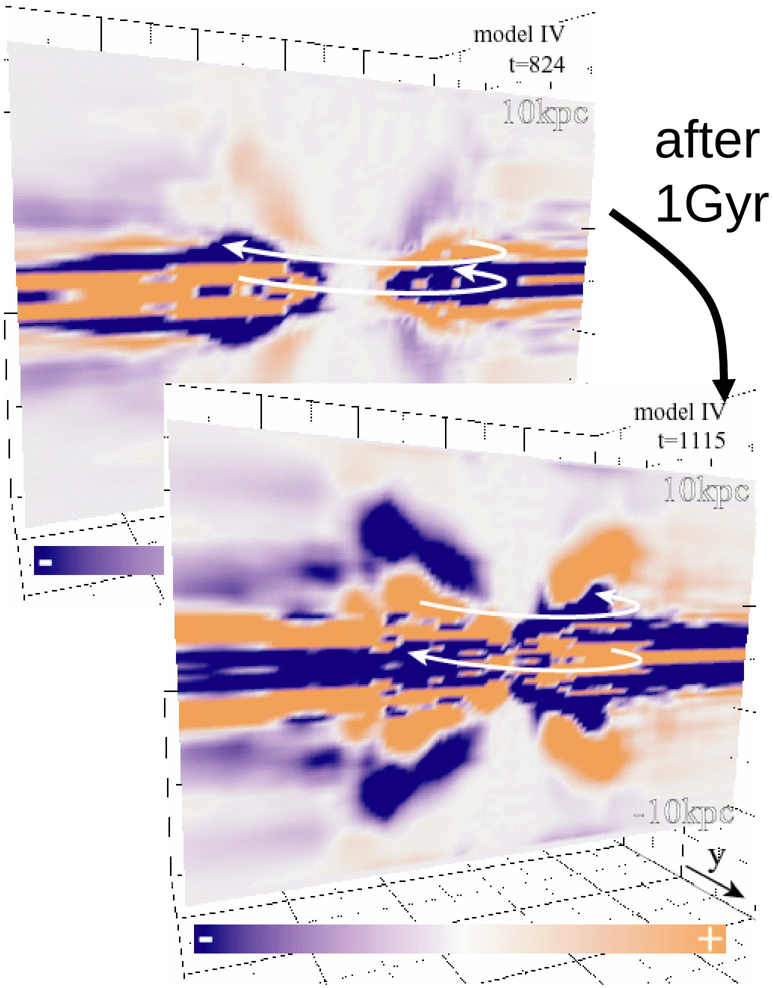


Distribution of azimuthal filed at r=10kpc at t=3Gyr

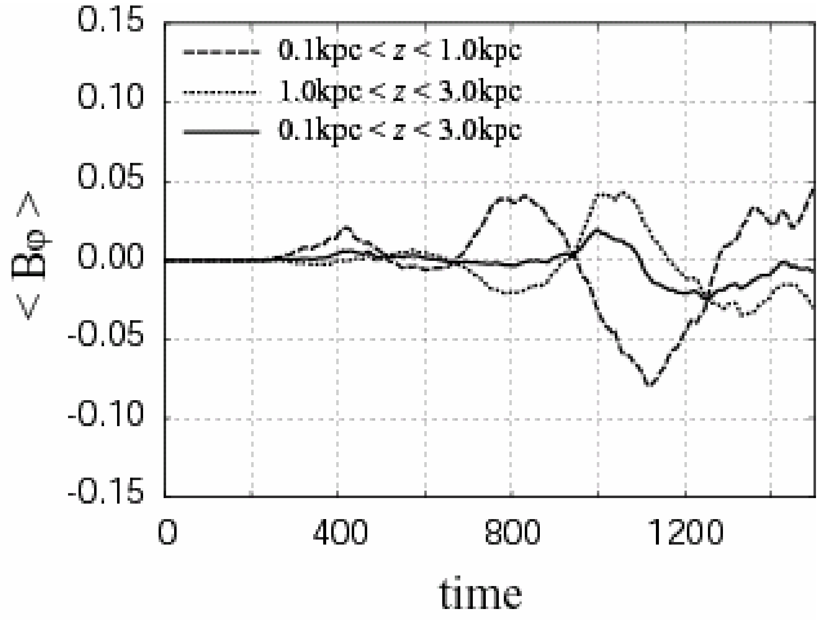
Motion of the Wavefront of Rising Magnetic Flux



Numerical Results for a Model with **β** =1000



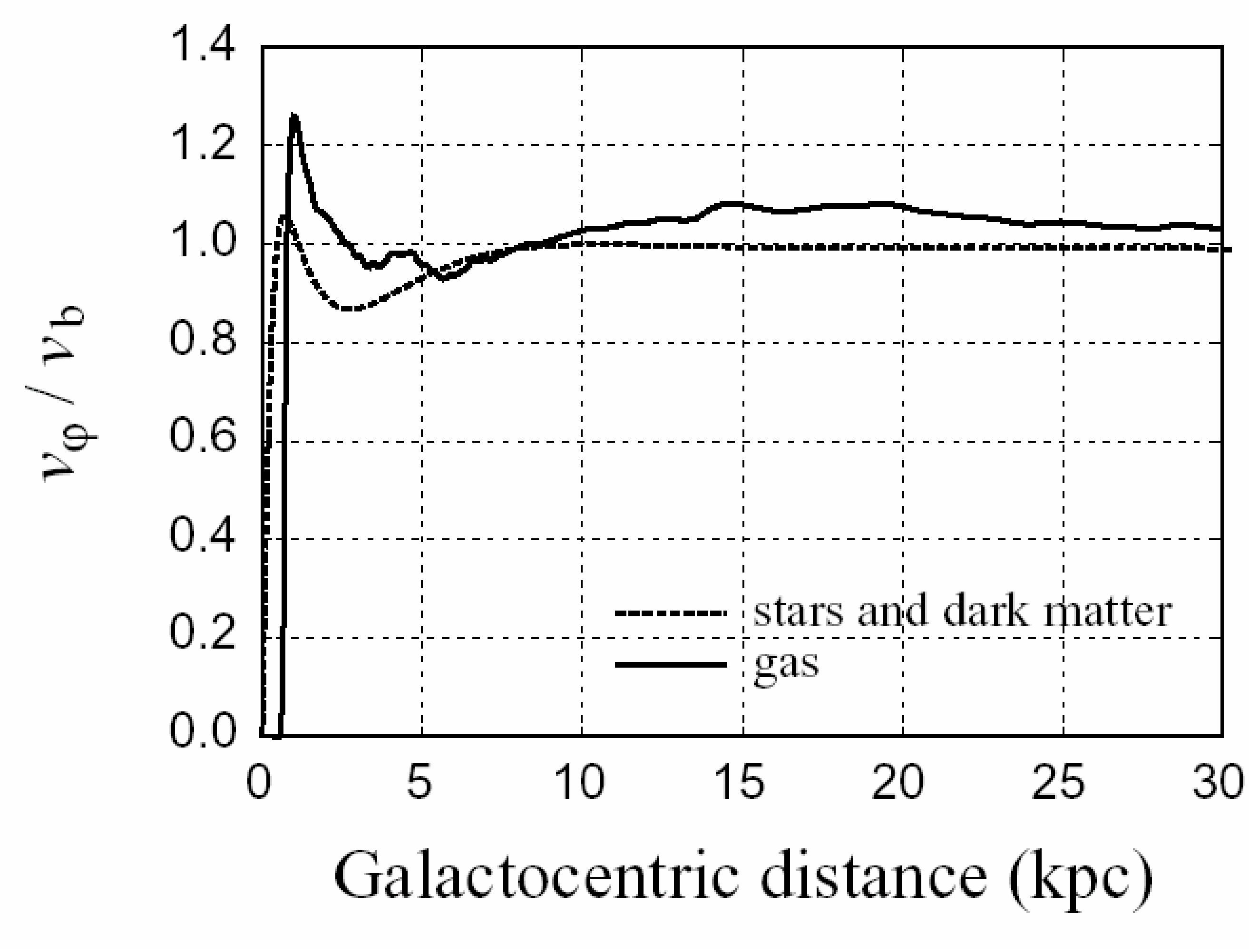
after
1Gyr…



Time variation of mean azimuthal magnetic field

At 5kpc < r < 6kpc

Rotation Curves for Stars/Dark matter and Gas



Discussion

- Magnetic field strength
  - Amplification of magnetic field saturates when $\boldsymbol{\beta} \sim 10$. The final field strength ($\sim \boldsymbol{\mu}$G) is smaller than the Galactic magnetic field
  - Non-axisymmetric gravitational potential, Supernova explosions, and/or cooling of the interstellar gas may further amplify magnetic fields
- Infall of the interstellar gas
  - Interstellar gas loses angular momentum by Maxwell stress and infalls with accretion rate 0.001M_sun/yr when the initial torus has 5*10^8 M_sun

Summary

- We studied the stability of the galactic spiral shock and showed by local and global simulations that even when the magnetic fields are included, wiggle instability grows.
- 3D global MHD simulations of the galactic gas disks under axisymmetric gravitational potential showed that μG magnetic fields are maintained
- The direction of azimuthal magnetic fields reverses both in space and time.
- Other mechanisms such as non-axisymmetric gravitational potential and/or supernova explosions may further amplify magnetic fields.